

NAL PROPOSAL No. 6

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200 GeV PROTON PROTON ELASTIC SCATTERING
AT HIGH TRANSVERSE MOMENTUM

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June 5, 1970

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This is a proposal to study p-p elastic scattering at the highest possible P_{\perp}^2 at NAL, using a CH_2 or H_2 target placed directly in the extracted beam and a double arm spectrometer. We expect to be able to set an upper limit at the level

$$\frac{d\sigma/dt}{d\sigma/dt)_{t=0}} \approx 10^{-14}$$

This would be sufficient to determine if there are exactly three regions in the p-p interaction with considerable precision.

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II. Physics Justification:

This experiment would measure the proton proton elastic scattering cross section at the highest possible P_{\perp}^2 . Previous experiments at CERN¹, BNL², ANL³, and LRL⁴ have measured out to 90° at the highest available energies. It is generally true that these four accelerators have been used more or less to their limits for this measurement. Similar experiments are not presently possible at Serpukhov because of the lack of a slow extracted beam and of long straight sections in the ring itself and they are not possible at the CERN ISR because the interaction rate is down by at least 10^6 relative to NAL.

There is at present no fundamental theory which has been successful in explaining the dependence of the proton proton elastic scattering cross section on momentum and angle. Perhaps this is because the measurements have been made with such small errors over a cross section range of 10^{-11} or 10^{-12} . Thus these measurements may well be one of the most stringent tests of any theory of strong interactions.

There have instead been many parameterizations and phenomenological fits to the data. One such fit proposed in 1967 consists of plotting the differential cross section $\frac{d\sigma^+}{dt}$ ⁵, against the quantity $\beta^2 P_{\perp}^2$ where β is the c.m. velocity. This variable is suggested by an optical model with an interaction region which is a Lorentz contracted sphere. The t in $\frac{d\sigma^+}{dt}$

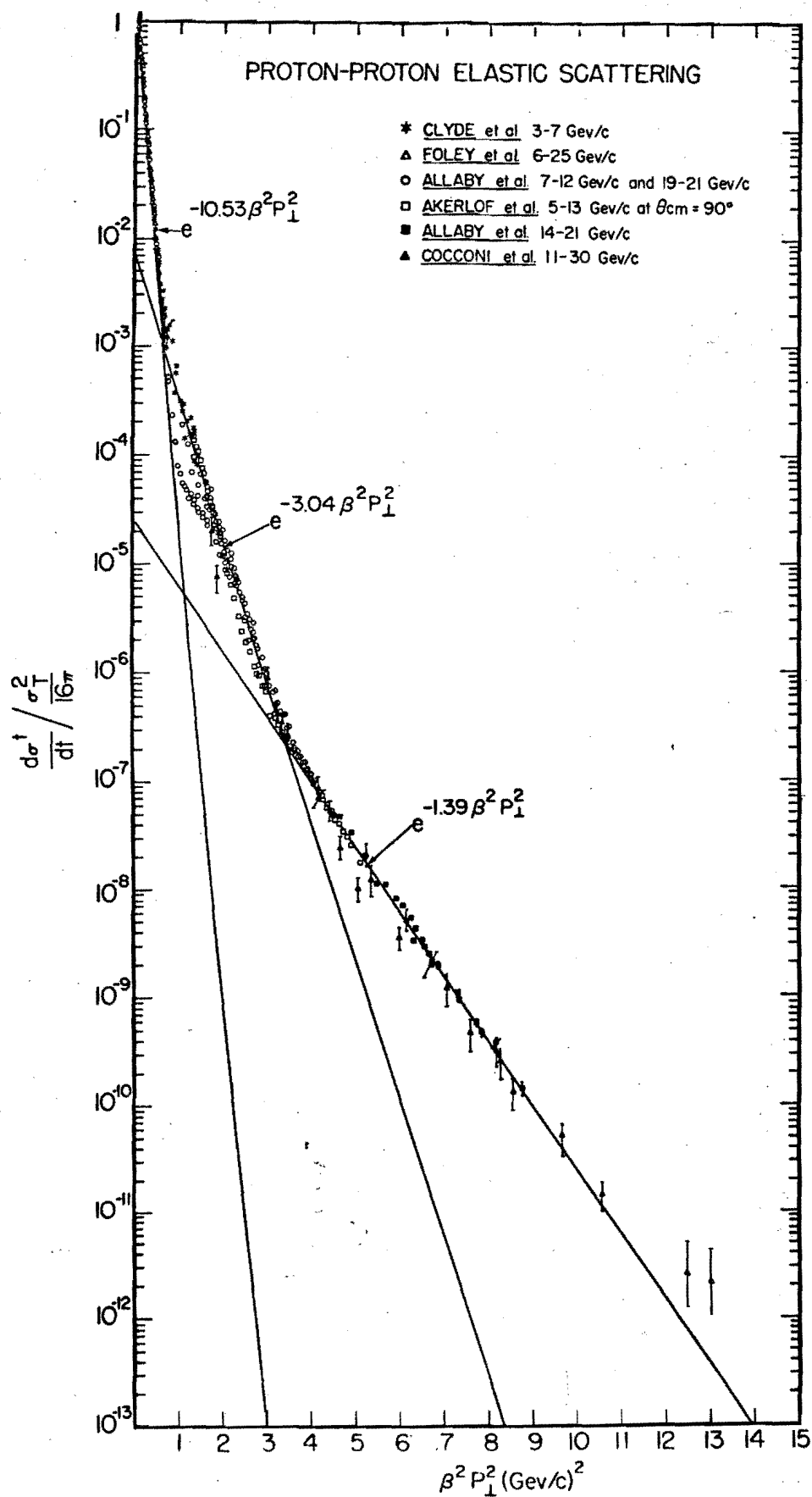


FIG 1

indicates that some attempt⁵ was made to consider the effects of particle identity in proton proton scattering near 90° . This plot is shown in Fig. 1 which contains all data above 3 GeV available up to 1970.

The most dominant feature of the cross section is the existence of three remarkably separate regions. In the 1st and 3rd regions all energy dependence or "shrinkage" appears to be removed so far, but in the 2nd region there is still some sort of energy dependence, which is not understood.

These three regions have been interpreted as evidence for:

- a. Three spatial regions in the p-p interaction of radii .9f, .5f and .33f.
- b. Single, double, and triple scattering as in the Glauber model of proton-deuteron scattering.
- c. The opening of new production channels;
specifically: region 1 - pion production;
region 2 - strange particle production;
region 3 - baryon antibaryon pair production.

The advocates of the multiple scattering model point out that there should also be quadruple scattering and thus a fourth region and point to the last two BNL points which lie well above the line. Unfortunately these points have such large errors that they don't settle this question. Other theorists especially Cerulus, Martin and Kinoshita⁶ have pointed out that if the cross section continues to drop as fast as

$$\frac{d\sigma}{dt} \sim e^{-1.4\beta^2 P_1^2} \quad (1)$$

then for fixed angle this is essentially an e^{-s} dependence which raises some problems concerning the analyticity of the scattering amplitude. If however there were a 4th region and then a 5th region and so on, then there would be no problem.

However the physics justification for this experiment is independent of any particular model or fit. It is clearly important to study the behavior of strong interactions at the highest P_1^2 possible. A violent probe such as this must give insight into the structure of strong interactions.

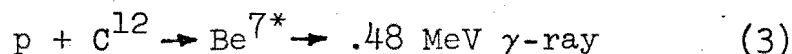
III. Experimental Arrangement

We propose to measure the cross section by placing a CH_2 or liquid H_2 target directly in the extracted beam. The two scattered protons will each be detected by one arm of a double arm spectrometer.

The cross section $\frac{d\sigma}{d\Omega}$ is determined from the equation

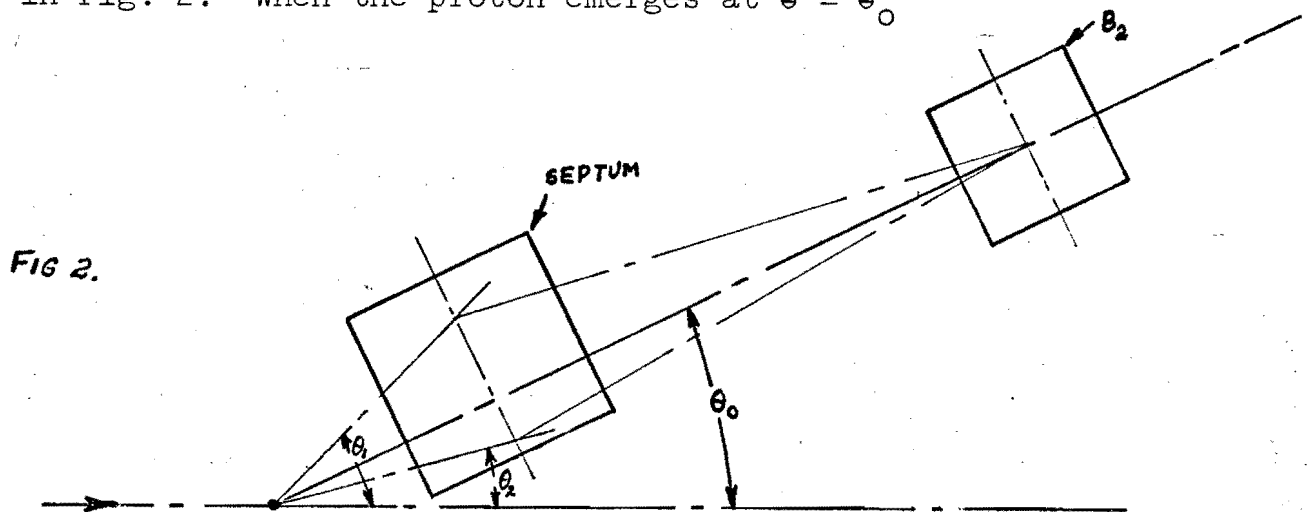
$$\text{Events} = I_0 N_T \frac{d\sigma}{d\Omega} \Delta\Omega \quad (2)$$

where N_T is the number of target particles/cm². The quantity I_0 is the incident beam intensity which can be determined by a radiochemical analysis of the CH_2 target looking for the spallation reaction



The Be^{7*} nucleus decays with a 77.5 day mean life which is very convenient for counting and rechecking.

The number of events will be determined by the coincidences between the two arms of the double arm spectrometer. Each spectrometer consists of magnets for angle and momentum analysis and scintillation counters to detect the protons and define the solid angle $\Delta\Omega$. An important part of each spectrometer is the septum magnet placed near the target. This acts as a steering magnet and allows protons scattered at various angles to be steered into the spectrometer without physically moving any magnets or counters. The basic concept is shown in Fig. 2. When the proton emerges at $\theta = \theta_0$

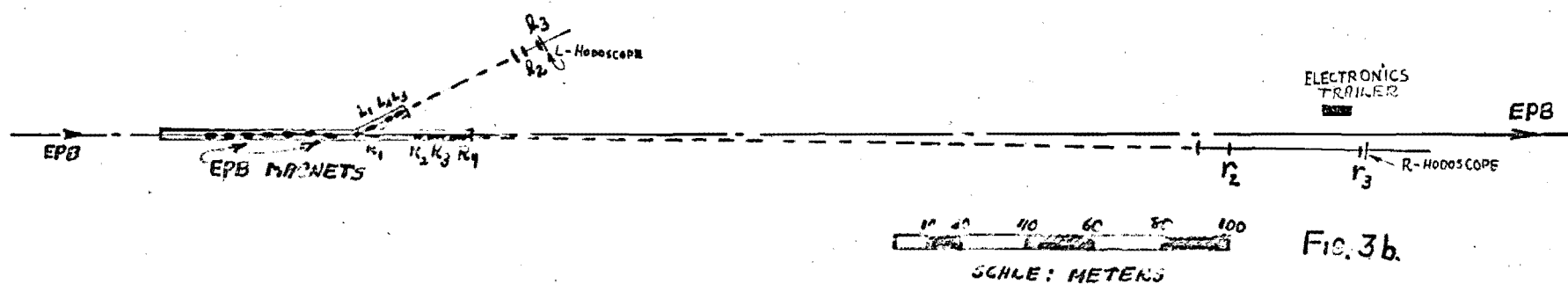
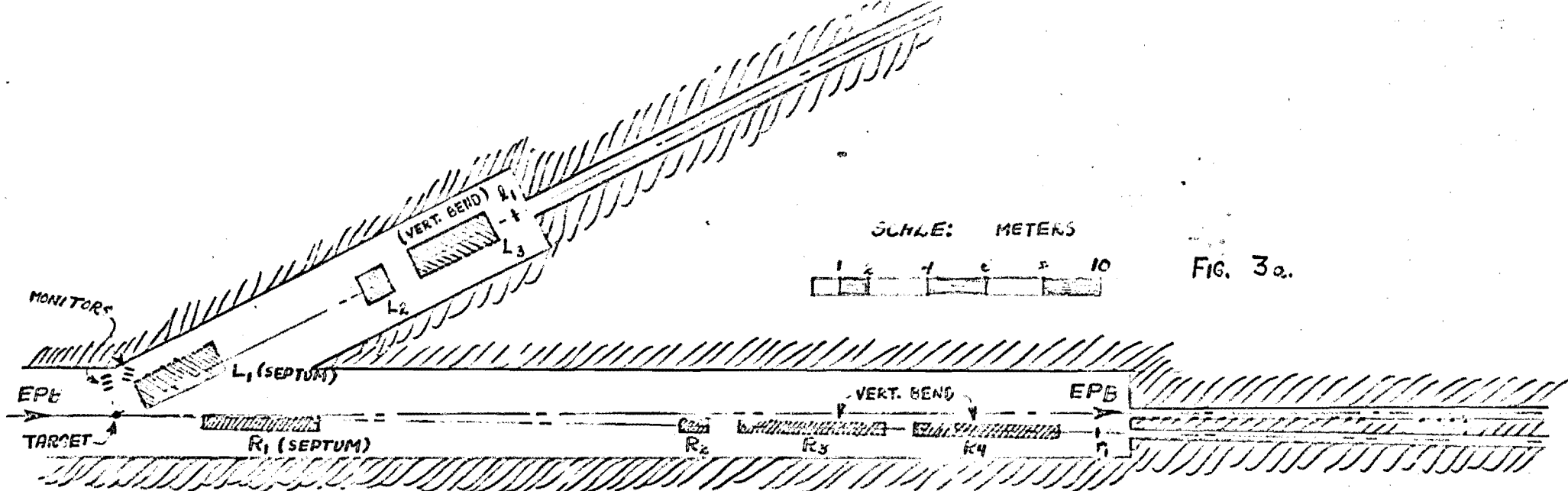


then the septum and B_2 are turned off and the proton goes right down the center of the spectrometer. If however $\theta_1 > \theta_0$ then the septum is set to bend inward and B_2 is set so that it steers the proton along the central axis of the spectrometer. Similarly if $\theta_2 < \theta_0$ then the polarities of the septum and B_2 are reversed so that the proton is bent outward and into

the spectrometer. This technique which has been used on several experiments^{3,7} allows protons scattered over a wide range of angles to be detected with a fixed spectrometer by merely varying the magnet currents.

After emerging from the B_2 magnet in a narrow cone the protons in each spectrometer are then bent vertically up as shown in Fig. 3. This provides the momentum analysis and also gets the protons up out of the tunnel and to ground level where they can be detected by counters with low singles rates. As shown in Fig. 3 all magnets can be contained in a normal main ring section of the EPB tunnel except for the magnets on the large angle side which we propose to place in an additional side section of main ring tunnel ~ 40 feet long and coming out at an angle of 450 milliradians. We would also require two pipes tunneling up 17 feet from beam height to ground level (one of 2 foot diameter and 130 feet long at an angle of 130 millirad and the other of 1 foot diameter and 700 feet long at an angle of 25 millirad). We would also require the main ring tunnel section of the EPB to be long enough downstream of our target to accommodate our high momentum septum magnets (~ 100 feet). These modifications of the main EPB tunnel are not free but we believe not excessively expensive since they utilize the main ring tunnel modules.

The CH_2 or H_2 target will be placed downstream of the EPB magnets in a tunnel section of the EPB. Thus all the radiation will go forward into the dirt shielding surrounding



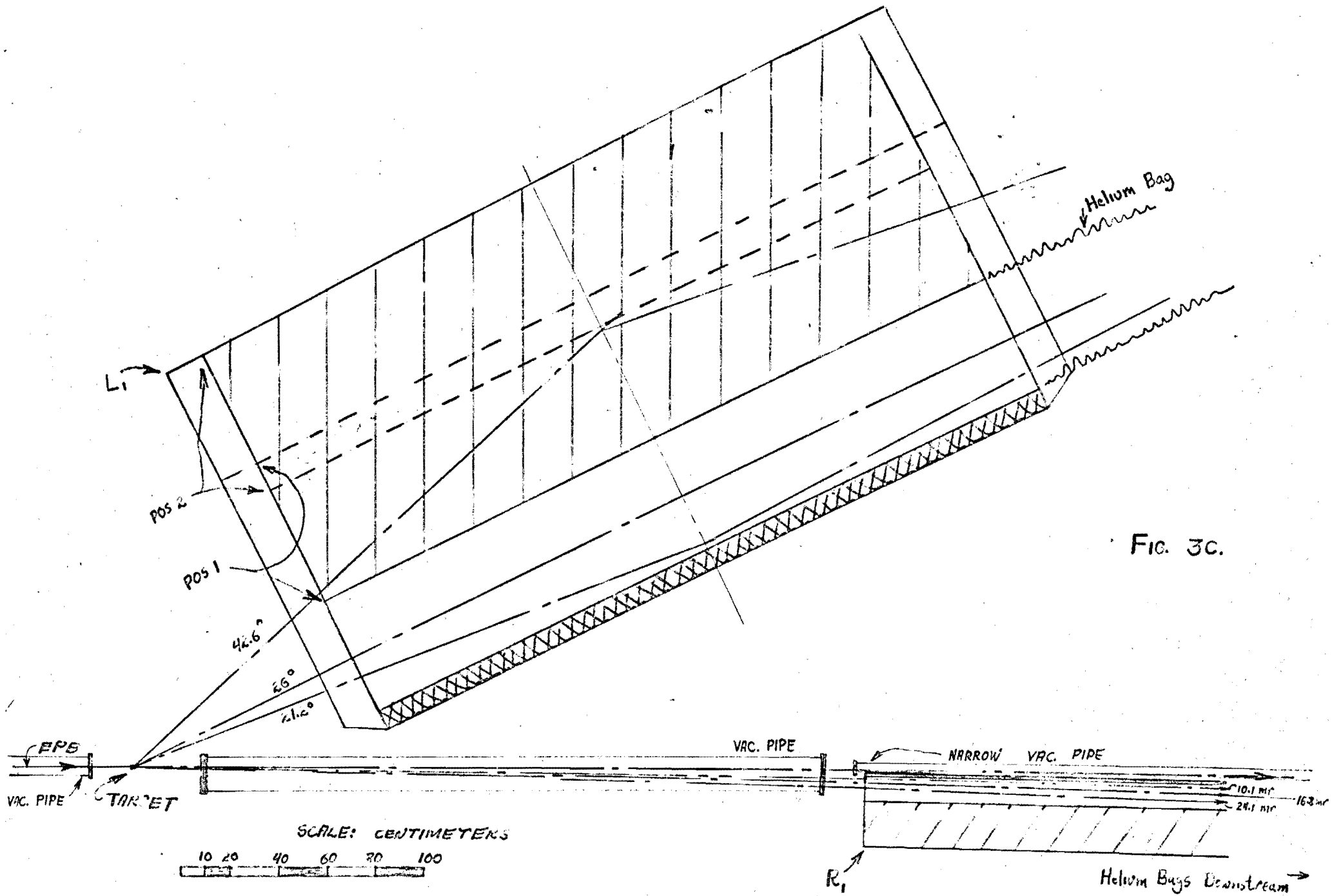


FIG. 3c.

a pipe section of the EPB, and will not cause radiation damage to any active elements of the EPB tunnel. We would prefer a 1 or 2 cm long CH_2 target (1 cm x 1 cm cross section). This gives reliable monitoring via the Be^{7*} reaction and the high radiation problems are easier to handle than with liquid H_2 which might boil excessively causing a change in the density. The main problem with CH_2 is it scatters the beam more and could cause some problems downstream in controlling the beam. We think that with a 2 cm target which has 4% of a collision length and radiation length these problems are not excessive. If they are judged excessive we would then use a 4 cm H_2 target (1% collision length and $\frac{1}{2}\%$ radiation length) but it would then be much more important to have the beam defocused as much as possible at the point where it hits our target. If we use CH_2 targets we would have a remotely controlled wheel with perhaps 30 CH_2 targets on it so that no target would receive sufficient radiation to lose more than a few percent of its hydrogen.

We plan to cover the P_{\perp}^2 range from approximately $P_{\perp}^2 = 4 \rightarrow 20 \text{ (GeV/C)}^2$. It is necessary to have magnets of sufficient bending power to steer and momentum analyze the protons at both extremes of this range. A kinematics table is shown for 200 GeV/C proton proton elastic scattering in Table 1. As shown in Fig. 3 the two central angles for the two spectrometers were chosen to be $\theta_o = 26^\circ$ and $\theta_o = .96^\circ$. We can then

INEMATICS FOR P-P ELASTIC COLLISION AT 200 BEV/C

= 377.067

ETA= 0.9953

AMMA= 10.3480

TABLE 1

$P_1^2 (\text{GeV}/c)^2$	θ_{CM}	$\theta^R (\text{degrees})$	$P^R (\text{GeV}/c)$	BETA	J^R	$\theta^L (\text{degrees})$	$P^L (\text{GeV}/c)$	BETA	J^L	
2	THETA	THETA	P	LAB	J*	THETA	THETA	P	BETA	J*
(PT)	C-M	LAB	LAB	LAB		C-M	LAB	LAB	LAB	
0.000	0.00	0.000	0.000	0.0000	0.000	180.00	0.000	0.000	0.0000	0.000
0.028	1.00	0.048	199.985	1.0000	428.263	181.00	84.840	0.169	0.1776	0.003
0.114	2.00	0.097	199.940	1.0000	428.070	182.00	79.761	0.343	0.3431	0.007
0.256	3.00	0.145	199.864	1.0000	427.745	183.00	74.838	0.524	0.4876	0.011
0.454	4.00	0.193	199.758	1.0000	427.293	184.00	70.132	0.717	0.6071	0.016
0.709	5.00	0.242	199.621	1.0000	426.711	185.00	65.686	0.924	0.7018	0.022
1.020	6.00	0.290	199.455	1.0000	426.001	186.00	61.528	1.149	0.7746	0.030
1.387	7.00	0.339	199.258	1.0000	425.163	187.00	57.670	1.394	0.8295	0.039
1.809	8.00	0.387	199.032	1.0000	424.199	188.00	54.110	1.660	0.8706	0.050
2.285	9.00	0.436	198.775	1.0000	423.107	189.00	50.840	1.950	0.9011	0.064
2.816	10.00	0.484	198.488	1.0000	421.891	190.00	47.844	2.264	0.9238	0.082
3.400	11.00	0.533	198.172	1.0000	420.550	191.00	45.103	2.603	0.9408	0.103
4.037	12.00	0.582	197.825	1.0000	419.083	192.00	42.597	2.969	0.9535	0.128
4.726	13.00	0.631	197.449	1.0000	417.497	193.00	40.304	3.361	0.9632	0.159
5.466	14.00	0.680	197.044	1.0000	415.787	194.00	38.204	3.780	0.9705	0.195
6.256	15.00	0.729	196.609	1.0000	413.959	195.00	36.280	4.227	0.9762	0.237
7.095	16.00	0.778	196.144	1.0000	412.008	196.00	34.513	4.701	0.9807	0.287
7.983	17.00	0.827	195.651	1.0000	409.945	197.00	32.887	5.203	0.9841	0.345
8.918	18.00	0.877	195.129	1.0000	407.764	198.00	31.389	5.733	0.9869	0.412
9.898	19.00	0.926	194.578	1.0000	405.469	199.00	30.005	6.291	0.9891	0.489
10.924	20.00	0.976	193.998	1.0000	403.060	200.00	28.725	6.877	0.9908	0.578
11.993	21.00	1.026	193.389	1.0000	400.544	201.00	27.538	7.491	0.9922	0.678
13.105	22.00	1.076	192.753	1.0000	397.917	202.00	26.434	8.132	0.9934	0.791
14.257	23.00	1.126	192.088	1.0000	395.184	203.00	25.407	8.801	0.9944	0.918
15.449	24.00	1.177	191.395	1.0000	392.345	204.00	24.448	9.497	0.9952	1.061
16.679	25.00	1.227	190.675	1.0000	389.404	205.00	23.552	10.221	0.9958	1.220
17.946	26.00	1.278	189.927	1.0000	386.363	206.00	22.713	10.971	0.9964	1.397
19.248	27.00	1.329	189.152	1.0000	383.224	207.00	21.926	11.749	0.9968	1.593
20.583	28.00	1.380	188.350	1.0000	379.988	208.00	21.186	12.554	0.9972	1.810
21.950	29.00	1.432	187.521	1.0000	376.660	209.00	20.489	13.385	0.9976	2.048
23.347	30.00	1.483	186.665	1.0000	373.239	210.00	19.832	14.242	0.9978	2.309

calculate the necessary field integrals in the two septums for the two extreme cases.

P_{\perp}^2 (GeV/C) ²	P_{Lab} (GeV/C)	θ_{Lab} (degrees)	$\theta - \theta_0$ (degrees)	$P(\theta - \theta_0)$ GeV/C degrees	1.33 $P(\theta - \theta_0)$ GeV/C degrees	$\int B \cdot dl$ KG- meters
20	12.55	21.2	-4.8	60.2	80	47
	188.4	1.38	.42	79.1	105	62
4	2.97	42.6	16.6	49.3	66	39
	198.2	.58	-.38	75.3	100	59

The factor 1.33 comes from the fact that the distance from the second magnet to the septum is 3 times the distance from the target to the septum. Thus we see that with two 16 kilogauss septum magnets of 3 meters (L_1) and 4 meters (R_1) we can steer all protons into our spectrometer for this entire P_{\perp}^2 range. The L_2 and R_2 magnets need only be 1 meter long since they only bend by 1/4 the angle of L_1 and R_1 .

The L_3 and R_3 - R_4 magnets then bend the particles vertically for momentum analysis. These must have enough $\int B \cdot dl$ to handle the maximum momentum on each side.

Magnet	P_{Max}	Vertical Bend	(θ)	$P_{Max} \theta$	$\int B \cdot dl$
	GeV/C	degrees		GeV/C- degrees	KG- meters
R_3 - R_4	198.2	1.43		284	166
L_3	12.55	7.5		94	55

Thus we require R_3 - R_4 to each be a 5-meter magnet of 17 kilogauss and L_3 to be a 3-meter magnet of 18.5 kilogauss. All magnets will be described in more detail in Sect. IV.

We next discuss the question of resolution in θ and P . We will define the solid angle ($\Delta\Omega$) on the low momentum side (L) since the Jacobian is so much larger on this side. The high momentum side (R) will then be overmatched to accept a larger solid angle. The defining ϕ_3 -counter will be about 2 ft. x 2 ft. at 200 feet from the target so that $\Delta\Omega_{\text{Lab}}^{\text{L}}$ will be 10^{-4} steradians. On the other (R) side the final counter r_3 will be about 10 inches x 10 inches at 1000 feet from the target for an overmatched $\Delta\Omega_{\text{Lab}} = 7 \cdot 10^{-7}$ steradians. The matched $\Delta\Omega_{\text{Lab}}$ varies between $(\Delta\Omega_{\text{Lab}}^{\text{R}})_{\text{matched}} = \frac{J_{\text{L}}}{J_{\text{R}}} \Delta\Omega_{\text{Lab}}^{\text{L}} = .32 \cdot 10^{-7} \rightarrow 4.5 \cdot 10^{-7}$ steradians.

We will probably use 10 x 10 hodoscopes of scintillation counters on each side to improve the resolution. This would give:

$$\Delta\theta_{\text{Lab}}^{\text{L}} \approx 1 \text{ mr} \qquad \Delta\theta_{\text{Lab}}^{\text{R}} \approx .07 \text{ mr} \qquad (4)$$

$$\Delta P/P)^{\text{L}} \approx \pm .4\% \qquad \Delta P/P)^{\text{R}} \approx \pm .15\% \qquad (5)$$

We feel that this resolution would be sufficient to discriminate against inelastic events and events from carbon in the CH_2 target. This can be tested by taking runs with a carbon target replacing the CH_2 target. In a similar experiment at ANL³ an upper limit of 0.1% was set on events of this type.

We next calculate the estimated counting rate at various values of P_{\perp}^2 . We estimate the value of the cross section $X \equiv \frac{d\sigma/dt}{d\sigma/dt}_{\theta=0}$ from Fig. 1. We assume an intensity of:

$$I_0 = 1 \cdot 10^{13} \text{ protons/sec} = 3.6 \cdot 10^{16} \text{ protons/hour} \quad (6)$$

The center of mass solid angle is given by:

$$\Delta\Omega_{\text{cm}} = J^L \Delta\Omega_{\text{Lab}}^L = 10^{-4} J^L \quad (7)$$

The number of target particles/cm² is given by:

$$N_T = N_0 \rho t \quad (8)$$

where N_0 (Avogadro's Number) is $6.02 \cdot 10^{23}$, ρ is the density of hydrogen protons in $\text{CH}_2 = .13$ and t is the target length which we take as 2 cm. Then we get

$$N_T = (6.02 \cdot 10^{23})(.13)(2) = 1.6 \cdot 10^{23} \frac{\text{protons}}{\text{cm}^2} \quad (9)$$

Similarly if we note that $d\sigma/dt_{\theta=0} \approx 10^{-25}$ then we get that

$$\begin{aligned} \frac{d\sigma}{d\Omega}_{\text{cm}} &= \frac{P^2}{\pi} \frac{d\sigma}{dt} = \frac{P^2}{\pi} \frac{d\sigma}{dt}_{\theta=0} X \\ &= \frac{100}{\pi} 10^{-25} X \\ &= 3 \cdot 10^{-24} X \end{aligned} \quad (10)$$

These numbers all go into the equation for the number of events/hour.

$$\begin{aligned}
 \text{Events/hour} &= I_0 N_T \frac{d\sigma}{d\Omega} \Delta\Omega \text{ cm} \\
 &= (3.6 \cdot 10^{16}) (1.6 \cdot 10^{23}) (3 \cdot 10^{-24} \text{ X}) (10^{-4} \text{ J}^L) \quad (11) \\
 &= 2 \cdot 10^{12} \text{ J}^L \text{ X}
 \end{aligned}$$

For various values of P_{\perp}^2 we tabulate J^L and X and then the counting rate is:

P_{\perp}^2	J^L	X	$\frac{\text{Events}}{\text{hour}}$	$\frac{\text{Events}}{\text{day}}$
4	.13	10^{-7}	$2 \cdot 10^4$	$5 \cdot 10^5$
10	.5	$2 \cdot 10^{-11}$	20	500
12	.8	$3 \cdot 10^{-12}$	5	125
15	1.0	$10^{-12} \rightarrow 2 \cdot 10^{-14}$	$2 \rightarrow .04$	$50 \rightarrow 1$
20	1.8	$2 \cdot 10^{-13} \rightarrow 10^{-16}$	$.4 \rightarrow 2 \cdot 10^{-4}$	$10 \rightarrow .005$

Clearly our maximum P_{\perp}^2 depends on whether or not the cross section breaks again. However we can set a limit on the minimum measurable cross section. If we call the minimum upper limit a rate of one event per day then we get a level of approximately 10^{-14} below the forward cross section.

In the range from $P_{\perp}^2 = 4 \rightarrow 20 \text{ (GeV/C)}^2$ we would make approximately 30 measurements with spacing and statistics that increase with increasing P_{\perp}^2 . We would average about two days of running at each point for a total of 2 months of data running at $I_0 = 10^{13}/\text{sec}$. Obviously most of the points in the range $P_{\perp}^2 = 4 \rightarrow 10$ could be run with considerably less intensity and a thinner target. Clearly this experiment can run simultaneously with the main target station downstream since

it only depletes the beam by a few % and runs at 200 GeV/c.⁸

We will be ready to start taking data in the Fall of 1972.

We expect several more young scientists at the student and postdoc level to join this experiment around Fall of 1971.

IV. APPARATUS:

In this experiment there are four types of equipment that will be required:

1. Detection counters and electronics.
2. Magnets, power supplies, and vacuum pipes.
3. Targets.
4. Changes in the EPB tunnel.

We will discuss them separately.

1. Detection equipment:

We expect to provide essentially all detectors and electronics equipment. A major fraction of this equipment will be used on an experiment at the CERN ISR starting July 1971. We expect that experiment to have finished by Spring 1972, and will return the equipment to Chicago well before Fall of 1972.

In the unlikely event that the ISR schedule is substantially delayed, we would duplicate all the specialized items and possibly borrow standard scalers and logic from PREP or SHELF at ANL.

The detection equipment is quite simple, consisting only of scintillation counters and logic circuitry. The hodoscopes will

probably not require a computer.

2. Magnets etc.:

We require a total of seven magnets and seven power supplies which are listed in table 2. Four of these magnets, L_2 , L_3 , R_3 , and R_4 can probably be standard NAL beam magnets. We could certainly change our parameters a little to conform to the NAL standards when they become firm.

The other three magnets, L_1 , R_1 and R_2 are all septums. We think that they would be useful for later experiments and we would hope that NAL would pay for them. We are again prepared to modify them somewhat if that would make them more generally useful. We are also prepared to contribute to the design of these magnets, if that is agreeable to NAL. We roughly estimate the total cost of L_1 , R_1 and R_2 at \$100,000. The R_1 magnet might become too radioactive to be useful for future experiments.

If NAL does not consider such septums useful we could request additional funding from the AEC to build them ourselves. However, we are not very enthusiastic about this approach.

We think the power supplies are fairly standard and could be provided by NAL.

The modifications to the EPB vacuum pipe and the helium bags for the length of the two spectrometers would hopefully be provided by NAL.

Table 2 Magnets

MAGNET	GAP			OVERALL			MAX B ₀ Kilogauss	COMMENTS
	height	width	length	height	width	length		
	cm	cm	m	m	m	m		
L ₁	5	50	3	1.10	1.15	3.3	16	8 cm septum
L ₂	≥ 12	≥ 20	1	Any Standard Magnet			12	
L ₃	≥ 16	≥ 30	3	.8	1	3.75	18.5	Possibly standard magnet
R ₁	2	10	4	.45	.30	4.3	16	1.5 cm septum
R ₂	5	5	1	.2	.2	1.3	16	5 cm septum
R ₃ -R ₄	≥ 5	≥ 10	5	.3	.6	5.4	17	Probably standard magnets

MAGNET	EST. WEIGHT TONS	EST. COST	EST. MAX. CURRENT AMPS	EST. MAX. VOLTAGE VOLTS	EST. POWER KILOWATTS
L ₁	55	\$55,000	900	400	360
L ₂	-	-	-	-	< 100
L ₃	30	(\$50,000) possibly std.	1000	360	360
R ₁	6	\$30,000	800	175	140
R ₂	~ 1	\$15,000	-	-	< 100
R ₃ -R ₄	9	(\$35,000) prob. std.	1000	425	425 each

3. Targets.

In the event that we use CH_2 targets we would provide these targets and the target changing mechanism. These targets would be quite radioactive so we would expect to work in close communication with the NAL radiation safety group.

The radiochemical analysis would probably be done by the radiochemistry group at Argonne. We have worked closely with this group in the past.

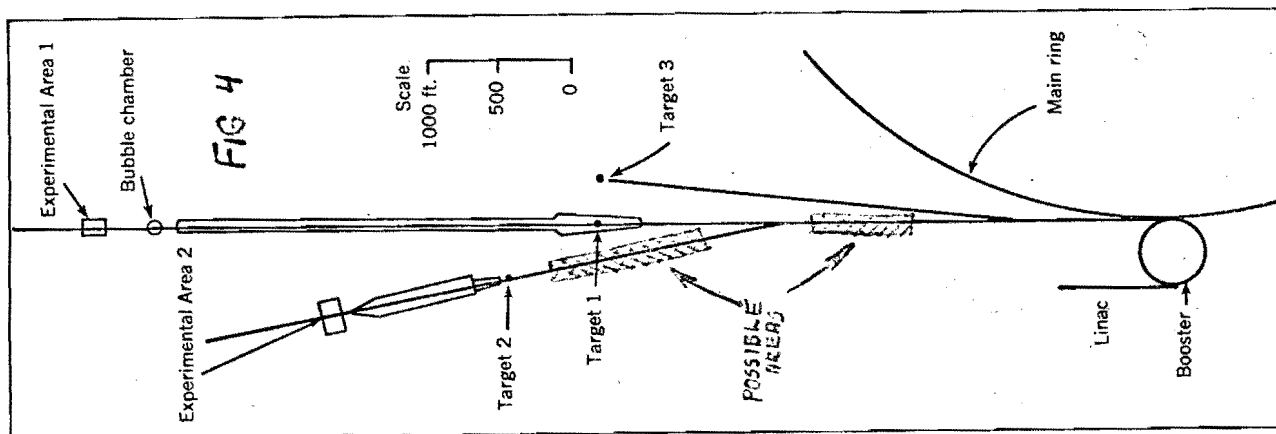
In the event that CH_2 is rejected and we use a liquid hydrogen target, then we would certainly need a helium refrigerated target. This would keep the temperature around 17° or 18°K and minimize boiling. This target could be built either at NAL or possibly by the ANL liquid hydrogen group which presently has several helium refrigerator units.

For the reasons mentioned in Sect. III we strongly prefer the CH_2 target.

4. Changes in the EPB Tunnel

As we mentioned in Sect. III we require some modifications to the EPB tunnel. We cannot list the exact modifications required since we do not have final plans for the EPB tunnel. We would work closely with NAL to find the area where our experiment could be installed with the minimum difficulty.

The experiment would probably fit best into one of the two general areas shown on Fig. 4.



The exact position would depend on avoiding interference with roads, buildings, and other obstacles, and the planned positions of the beam magnets along the EPB. The dimensions of our experiment are shown in Figs. 3a and 3b. They could of course be modified somewhat and the high momentum proton could come out on the left instead of the right.

In general the target should probably be placed immediately downstream of a set of the EPB quadrupoles as shown in Fig. 3b. We believe that the present EPB plan is to have some main ring modules (10 foot diameter) for these EPB magnets separated by beam pipes (~ 1 foot diameter) about 500 feet long. By placing our target immediately downstream of these quadrupoles we could utilize the ~ 500 feet of earth shielding to protect the downstream EPB magnets from radiation produced in our target.

As mentioned in Section III, we would require an additional

~100 feet of main ring modules beyond the end of the EPB magnets and about 40 more feet of modules coming out at an angle of 26° as shown in Fig. 3. Thus we would require an additional 140 feet of main ring modules. One way to estimate the cost of this is to note that the main ring of circumference 20614 feet was estimated (1968 Design Report, 16-6) to cost ~\$16.6 million. This would give:

$$\text{Cost} = \frac{140}{20614} \times \$16.6 \text{ Million} \approx \$113,000$$

The true cost might well be higher than this and would have to be estimated by NAL.

As seen from Table 2 our maximum DC power use would be about 1.9 megawatts. All of this would occur in the 140 foot tunnel section since there are no magnets outside of this area. The cost of this power will have to be estimated by NAL.

Our only other requirements are:

- a. Small patches of blacktop on which to place our scintillators and electronics trailer.
- b. Perhaps 10 KW of AC to our trailer which is fitted with a 440/110 transformer.
- c. Tents to cover our scintillators which we might provide, if necessary.

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